1 Introduction

This report documents BOE's investigation and root cause analysis ("RCA") of foaming events at the South Sioux City, NE Big Ox Energy anaerobic digester ("BOE SSC") and includes corrective actions for management to implement that address the causes of the issue, and that prevent or minimize recurrence of similar issues.

1.1 Overview of the Issue

A series of process disruptions, human resource management issues and equipment failures culminated in separate, coinciding events at BOE SSC.

Event # 1 was a foaming event / digestate spill and subsequent gas release, and
Event #2) was a hydraulic overload of the digesters stemming from the waste water treatment (WWT) system.

Listed herein are contributing factors in no particular order:

1. Management:
    a. BOE's customer management (feedstock intake) system allowed excessive deliveries of fats, oils and greases (FOGs) and a rapid increase in digester organic loading rate.
    b. Daily plant process loading communication was incomplete or lacking in some cases.
2. External Environment:
    a. A period of extreme rainfall, exceeding 25 inches per week at time, magnified the impact of the effluent discharge and delayed or extended clean up.
3. Process:
    a. Monitoring
        i. Feedstock metering: BOE failed to identify FOG loading levels that exceeded normal operating levels. BOE operator did not receive notification of elevated incoming FOG levels. Critical staff overseeing the feeding at plant lost visibility due to absence of these reports after recent leadership change.
    b. Hydraulic overload
        i. During the remediation of the initial foaming event, thousands of gallons of fresh water were introduced to distribute spray to break the foam outside the plant SCADA system, thus there was no control visibility of the fresh water effect on the total hydraulic load. This was compounded by the increased flow of GEM sludge that accompanied the GEM malfunction. Simultaneously, other unmetered feeds were added as part of the remediation effort.
4. Equipment – multiple equipment failures prior to and during foaming event:
    a. Mixers in Digester #1 were disabled, contributing to floating solids not properly entrained into digestate.
    b. Centrifuges were disabled weeks earlier necessitating addition of screw presses and process change. Repair underway but delayed for parts.
    c. Screw presses were new to facility/process but screw press operation was not optimized
    d. GEM/DAF was not operating properly and not able to adapt to process variation resulting in the WWT process overload.

2 Causes

2.1 Organic Loading Rate (OLR)

- Causal Factor #1: Excessive loading (organic loading rate or "OLR") of high-strength wastes containing fats, oils and greasy materials.
- Root Cause #1: The customer / provider delivered significantly more than the expected amount of product in a short time period.

Industry best practices suggest measured increases in daily OLR followed by acclimation periods. At the time of the Events, the baseline SSC OLR averaged approximately 100,000 lbs. of daily OLR into BOE SSC's total digester volume of ~ 4M gallons.

The maximum recommended OLR increase increment is approximately 4.0 lbs/100 gal of total digester volume (17,000 lbs. OLR at BOE SSC). The day-to-day variability in OLR in BOE SSC is high; precise control of the organic solids added to the digester is not possible.

During the weeks preceding the Events the average OLR more than doubled over a period of only a few weeks. Also, the composition of the increased organic load was high in fats, oils and greases. This large increase in high-fat organic load with no corresponding acclimation period gave rise to the microbial activity resulting in the excessive foaming.

- Correction Action #1: Improved characterization and ongoing monitoring of feedstock characteristics. Controls and procedures are being implemented that continually monitor the characteristics of the feedstocks fed into the digester and that apply statistical process control (SPC) to characterize the normal load-to-load variation in several key feedstock characteristics.

- Corrective Action #2: Controls and procedures are being implemented that continually monitor the OLR and apply statistical process control (SPC) to characterize the normal day-to-day OLR variation.

- Correction Action #3: Computational modeling based on improved feedstock characterization and monitoring of feedstock characteristics, digester feeds and flows, including rigorous mass and energy balances is under development and is being implemented. Computational modeling enables explicit and implicit SPC to characterize the normal process variation.

2.2 Management Processes – Communication

- Contributing Cause #1 – Feed Process communication disruption. A standard operating procedure in place immediately prior to the Events that was routinely followed by the SSC leadership team was not strictly followed.

- Corrective Action CC #1 – Improved communications include daily meetings specifically aimed at adherence to standard process. Engineering has been included in the daily discussions. Standard procedures have been revised and updated and all personnel have been thoroughly trained in revised procedures.

2.3 Equipment Malfunction

The Team also identified the following contributing cause.

- Contributing Cause #2 – There were multiple pieces of process equipment that failed prior to and during the Event. Mixers, specifically mixer #2 in digester #1 and the waste water centrifuges malfunctioned. The dissolved air floatation (DAF) system, specifically the GEM was also malfunctioning. Excessive loading from the failed centrifuges exacerbated process imbalances within the GEM.

- Corrective Action CC #2 – Additional mixing was installed to overcome the mixing inefficiency caused by malfunctioning mixer #2. Two new screw presses were installed to reduce the loading on the centrifuges. The process flow was improved, and the centrifuges were overhauled. Original equipment manufacturers (both Centrifuges and Gem/DAF systems) were brought in to recalibrate and rebalance process parameters for the repaired and/or replaced equipment.

2.4 Hydraulic Overload – Mass Balance

- Contributing Cause #3 – Sludge from the malfunctioning GEM system was rerouted to the digester along with fresh water and de-foaming agents. The increased hydraulic load to the digester system forced additional foam to escape from the digester.

- Corrective Action CC #3 – The effluent flow was redirected through the new screw presses and the polymer addition to the GEM was balanced and optimized through separation trials conducted off site using our digestate, by Centrisys to identify the optimal polymer additives to enhance separation at the Centrifuges. This substantially reduced loading on GEM system. Detailed accounting of all feeds and flows was performed and operations were corrected such that hydraulic overloading was eliminated. A dedicated BOE employee was assigned to run DAF system. Standard Operating Procedures to assure hydraulic loading remains in balance have been adopted.

3 Investigation Background

- The team gathered relevant facts through interviews, document reviews, and multiple walk-throughs of the location where the incident took place.
  - Parties interviewed are listed in Appendix A.
  - The documents reviewed are listed in Appendix B.
- Completing a thorough review of available data regarding all inputs and outputs into and out of the SSC digester system, including:
  - trucked-in waste,
  - additives,
  - force main flow,
  - fresh water flow,
  - DAF sludge recycle flow
  - DAF effluent flow
  - Hauled-out solids

  - cross-referencing feed stock characterization data to analyze the relevant characteristics and identify the causal factors and root causes of this issue.
- The team met numerous times to discuss and develop corrective actions to address each of the causes of the issue and to prevent recurrence.
- The team enlisted expert consultants to develop and deploy computational models that use rigorous mass, energy, biochemical conversion and flow balances for the SSC digester system. This effort included, but is not limited to:
  - Detailed analysis of all available feedstock analytical data
  - Comparison and cross-referencing of available analytical data to extensive public domain databases
  - Modeling and calibration of feedstock behavior, digester feeds and flows and biochemical processes
  - Development of structured data queries enabling translation of feedstock characteristic data and in-process manufacturing flow data into computational models
  - Development of modeling techniques to refine feedstock characteristic data through comparison to literature date

4 Computational Modeling Efforts

BOE SSC's parent company, Environmental Energy Capital LLC ("EEC") contracted development of a simulation model of BOE SSC to characterize and optimize plant operations and provide guidance on future design options, and to validate and quantify results of investigation of underlying causes of plant upsets. Development of the computational models and simulations was in-process when the 06/2018 foaming Event occurred. The models therefore incorporate both stable and Event conditions.

The computational models of BOE SSC include:

- An anaerobic digester model consisting of six equally sized continuous flow stirred tank reactors in series (three for anaerobic digester one, three for anaerobic digester 2) to approximate the plug flow nature
- The loading pattern and unique feedstock characteristics of the 14 most heavily loaded trucked-in wastes (accounts for 92% of trucked-in waste by weight)
- The loading pattern and estimated aggregate feedstock characteristics of 41 additional trucked-in wastes (accounts for 8% of trucked-in waste by weight)
- The flow pattern and wastewater characteristics of the influent SSC forced mains
- A dissolved air flotation model (the "GEM") with influent flow and proportional sludge flow control
- An influent equalization tank model with a base flow of 79,300 gpd (300 m^3/d)
- A centrifuge model with a constant centrifuge solids removal rate of 9,250 gpd (35 m^3/d)
- Data visualization of several key performance indicators including simulated methane production, effluent total suspended solids, and influent C to N ratio

The model was initially calibrated using a 90-day period of SSC feeds and flows input. The process data and was later validated against an expanded 218-day period. After a rigorous feedstock characterization effort, the model accurately predicted the methane production and flow biochemical dynamics of SSC over the first 130 days of the modeled period.

The BOE SSC model was developed using public domain and laboratory data, reference to technical literature, and thorough communication among the various parties. Much of the simulation and model development effort was directed towards data consolidation and feedstock characterization. The resultant version of the BOE SSC model includes all relevant unit processes with each anaerobic digester modeled as a three reactor in series unit which allows the for the approximation of plug flow behavior at a reasonable simulation speed. The model captures the trucked-in waste and influent forced-main dynamics at SSC and balances the solids destruction and hauled out pressed solids.

5 Conclusions

A model of the BOE SSC biogas plant was developed that includes all relevant unit processes (e.g. anaerobic digesters, solids separation equipment, input and internal flow dynamics). The BOE SSC model incorporates the loading dynamics of all trucked in wastes and provides a unique set of characteristics for each of the 14 highest loaded feedstocks during a 218-day period. The temporal variation in BOE SSC force main flow is accounted for with a one-hour resolution. Modifications to trucked in wastes and operating strategy can be readily implemented in the model, as can proposed or planned design upgrades.

The BOE SSC model predicted methane production for the first 130 days of a 218-day period (August 1, 2017-March 6, 2018), after which a reported foaming event occurred at BOE SSC, which prevented accurate prediction of pipeline injected natural gas. The model did predict total biogas production for the entire 218-day period as compared to a calculated estimation of total biogas provided by EEC colleagues.

The BOE SSC model revealed a likely cause of lower than expected methane production in February 2018 after recovery from the reported foaming event in December 2017. The decline in methane production is likely attributable to delivery gaps and lower loading rates of several high COD trucked in wastes.

Several simulated sensor blocks were incorporated into the BOE SSC model to allow for monitoring of key performance indicators such as C to N ratio, fatty acid concentration, and propionate to acetate ratio. The existing sensors can be supplemented with combination of state variables in the anaerobic digestion model.

Discrepancies between measured and modeled total suspended solids concentrations are potentially due to an overestimation of trucked in waste solids content in the model and/or an underestimation of centrifuge solids removal. Additional factors such as inaccuracies in TSS measurement or unaccounted solids discharges from the plant must also be

considered. An analysis of solids handling setpoint variation had minimal impact on predicted methane production rates.

Refinements to the model are possible with targeted laboratory measurements. However, the model in is sufficiently developed to assist in optimization of plant operations, guidance on future design options, and investigation of underlying causes of plant upsets.

6 Recommendations and Next Steps

6.1 Data Management

Efficient and robust data management is the key first step to optimize performance at SCC. We recommend deployment of the Monitoring and Control Platform (M&CP) at the BOE SSC plant to improve the management of biogas plant data. The M&CP is a suite of software tools that vastly improves the organization, accuracy, and completeness of data. Key functionalities include (1) integration of all relevant data streams into a single database, (2) the application of multivariate statistical methods to recognize and correct data outliers and fill sparse data sets, and (3) the ability to detect online data drift and sensor failures. An example application would be to integrate planned feedstock deliveries into the M&CP data stream, model those future deliveries, and forecast their effect on gas production and plant stability. The use of such a continuously updated online plant model would alert plant operators to potential violations of operating guidelines and avert process instabilities such as the foaming events periodically suffered at BOE SSC.

6.2 Feedstock Management

The majority of the effort during model development was directed towards characterization of the trucked in wastes delivered to BOE SSC. We recommend the development of a software tool to improve the efficiency of feedstock characterization and assessment. This proposed tool, which has been given the name "feedstock wizard" will be a user-friendly, standalone software application that accurately characterizes existing and potential biogas plant feedstocks with respect to their biomethane potential (BMP), handling recommendations, and potential effect on plant operations. The feedstock wizard will include an extensive library of public domain biogas feedstocks for comparison with new feedstock entries. The feedstock wizard will also facilitate the calculation of compatible feedstock characteristics from the feedstock library and new feedstock entries.

6.3 Plant Upgrade Modeling

The key design limitations noted at BOE SSC were a lack of equalization tank volume and limited capacity of the centrifuges used for sludge dewatering. As a model for the BOE SSC plant is further developed, it is possible to model planned or proposed process upgrades. Design scenarios to model include but are not limited to (1) replacement of the centrifuges with screw presses, (2) addition of dosing tanks for high strength feedstock equalization.